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# United States Patent [19]

## Islam

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### [54] BROADBAND SAGNAC RAMAN AMPLIFIERS AND CASCADE LASERS

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#### Related U.S. Application Data

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[52] U.S. Cl. .... **372/6; 372/21; 372/22; 372/70; 372/71; 372/72; 372/94; 372/99; 356/345; 359/115; 359/127; 359/134; 359/341; 359/345; 359/346; 385/39; 385/42; 385/122**

[58] Field of Search ..... **372/6, 21, 22, 372/27, 28, 69, 70, 71, 72, 39, 92, 94, 96, 97, 99, 106, 3; 356/345; 359/115, 127, 133, 134, 341, 345, 346, 122; 385/39, 42, 122, 47**

#### [56] References Cited

##### U.S. PATENT DOCUMENTS

4,964,131	10/1990	Liu et al.	372/6
5,497,386	3/1996	Fontana	372/18
5,513,194	4/1996	Tamura et al.	372/6
5,673,280	9/1997	Grubb et al.	372/3
5,778,014	7/1998	Islam	372/6

##### FOREIGN PATENT DOCUMENTS

0 265 233 A1 4/1988 European Pat. Off. .... 372/6

##### OTHER PUBLICATIONS

Sato et al., "A 1.6  $\mu\text{m}$  Band OTDR Using a Synchronous Raman Fiber Amplifier," IEEE Photonics Technology Letters, Aug. 1992, pp. 923-925.

Chernikov et al., "High-gain, monolithic, cascaded fibre Raman amplifier operating at 1.3  $\mu\text{m}$ ," Electronics Letters, Mar. 16, 1995, vol. 31, No. 6, pp. 472-473.

Dianov et al., "Demonstration of 1.3- $\mu\text{m}$  Raman Fiber Amplifier Gain of 25 dB at a Pumping Power of 300 mW," Optical Fiber Technology, Mar. 22, 1995, vol. 1, pp. 236-238.

Chernikov et al., "High-power, compact, high-efficiency, fiber laser source around 1.24  $\mu\text{m}$  for pumping Raman amplifiers," Technical Digest of the Optical Fiber Communications Conference, Feb. 1997.

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#### [57] ABSTRACT

This invention describes new developments in Sagnac Raman amplifiers and cascade lasers to improve their performance. The Raman amplifier bandwidth is broadened by using a broadband pump or by combining a cladding-pumped fiber laser with the Sagnac Raman cavity. The broader bandwidth is also obtained by eliminating the need for polarization controllers in the Sagnac cavity by using an all polarization maintaining configuration, or at least using loop mirrors that maintain polarization. The polarization maintaining cavities have the added benefit of being environmentally stable and appropriate for turn-key operation. The noise arising from sources such as double Rayleigh scattering is reduced by using the Sagnac cavity in combination with a polarization diversity pumping scheme, where the pump is split along two axes of the fiber. This also leads to gain for the signal that is independent of the signal polarization. Finally, a two-wavelength amplifier for 1310 nm and 1550 nm can be implemented by using a parallel combination of Raman amplifiers with shared pump lasers or by combining Raman amplifiers with erbium-doped fiber amplifiers. Combinations of the above improvements can be used advantageously to meet specifications for broad bandwidth, polarization independence, noise performance and multi-wavelength operation.

92 Claims, 17 Drawing Sheets

